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A conceptual framework for dryland aeolian sediment transport along the grassland–forest continuum: Effects of woody plant canopy cover and disturbance

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ABSTRACT

Aeolian processes are of particular importance in dryland ecosystems where ground cover is inherently sparse because of limited precipitation. Dryland ecosystems include grassland, shrubland, savanna, woodland, and forest, and can be viewed collectively as a continuum of woody plant cover spanning from grasslands with no woody plant cover up to forests with nearly complete woody plant cover. Along this continuum, the spacing and shape of woody plants determine the spatial density of roughness elements, which directly affects aeolian sediment transport. Despite the extensiveness of dryland ecosystems, studies of aeolian sediment transport have generally focused on agricultural fields, deserts, or highly disturbed sites where rates of transport are likely to be greatest. Until recently, few measurements have been made of aeolian sediment transport over multiple wind events and across a variety of types of dryland ecosystems. To evaluate potential trends in aeolian sediment transport as a function of woody plant cover, estimates of aeolian sediment transport from recently published studies, in concert with rates from four additional locations (two grassland and two woodland sites), are reported here. The synthesis of these reports leads to the development of a new conceptual framework for aeolian sediment transport in dryland ecosystems along the grassland–forest continuum.

The findings suggest that: (1) for relatively undisturbed ecosystems, shrublands have inherently greater aeolian sediment transport because of wake interference flow associated with intermediate levels of density and spacing of woody plants; and (2) for disturbed ecosystems, the upper bound for aeolian sediment transport decreases as a function of increasing amounts of woody plant cover because of the effects of the height and density of the canopy on airflow patterns and ground cover associated with woody plant cover. Consequently, aeolian sediment transport following disturbance spans the largest range of rates in grasslands and associated systems with no woody plants (e.g., agricultural fields), an intermediate range in shrublands, and a relatively small range in woodlands and forests. These trends are consistent with previous observations relating large rates of wind erosion to intermediate values for spatial density of roughness elements. The framework for aeolian sediment transport, which is also relevant to dust fluxes, wind erosion, and related aeolian processes, is applicable to a diverse suite of environmental challenges, including land degradation and desertification, dust storms, contaminant transport, and alterations of the hydrological cycle.

1. Introduction

Dryland ecosystems cover a substantial portion of the terrestrial biosphere (House et al., 2003). Vegetation cover is often relatively sparse and soils are often dry in these ecosystems relative to more mesic ecosystems because of less precipitation and greater evaporative demand (McPherson, 1997; Anderson et al., 1999; Whitford, 2002; Loik et al., 2004). A key consequence of sparser vegetation cover and drier soils is the potential for an increase in aeolian sediment transport and related processes of wind erosion and dust flux (Toy et al., 2002). Further, many dryland ecosystems are undergoing accelerated land degradation, which affects sediment redistribution and erosional loss through aeolian and fluvial processes (Schlesinger et al., 1990; Aguiar and Sala, 1999; Breshears et al., 2003; Peters et al., 2006). An improved understanding of aeolian processes is required to assess atmospheric, hydrologic, and biogeochemical processes (Miller and Tegen, 1998; Reynolds et al., 2001, 2006a,b,c; Peters et al., 2006), as well as to address a diverse suite of environmental challenges related to soil and water quality (Toy et al., 2002; Lal et al., 2003), land quality and productivity (Lal, 1996; Toy et al., 2002), and human health (Griffin et al., 2001; Whicker et al., 2006b).

Despite the fundamental importance of aeolian sediment transport and erosion processes in dryland systems, few studies have estimated

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aeolian sediment transport in the field, particularly for periods spanning multiple events over several months to a few years. Even fewer measurements have been reported for relatively undisturbed ecosystems. Notably, previous debates about rates of erosion in dryland ecosystems (and associated policy implications) have not directly addressed the large knowledge gap associated with rates of wind erosion, focusing instead primarily on water erosion (Crosson, 1995; Pimentel et al., 1995a,b; Nearing et al., 2000; Trimble and Crosson, 2000a,b).

Dryland ecosystems are extensive globally and encompass a diverse set of major types of vegetation that include grassland, shrubland, savanna, woodland, and forest (House et al., 2003). A first-order descriptor for these types of vegetation is the amount and stature of woody plant cover (Breshears, 2006). These dryland types of vegetation can be viewed collectively as a continuum of woody plant cover spanning from grasslands with no woody plant cover to forests with nearly complete woody plant cover—referred to as the grassland–forest continuum. The height of woody plants often increases with canopy cover along this conceptual gradient (Martens et al., 2000). Woody plants affect many ecosystem properties beneath the canopies and around them, and these effects can translate into trends along the grassland–forest continuum (Fig. 1A) for such properties as near-ground solar radiation (Martens et al., 2000) or soil water content (Breshears and Barnes, 1999). This perspective is relevant to numerous, diverse environmental issues such as desertification and forest restoration (Breshears, 2006). Notably, the height and spacing of woody plants are key determinants of surface roughness and associated factors that are fundamental to aeolian processes. The mean and variance of numerous ecosystem properties related to energy, water, and biogeochemistry (e.g., carbon) are hypothesized to exhibit trends along the continuum. Of particular relevance to aeolian sediment transport and associated wind erosion is that the variance of many ecosystem properties is hypothesized to be greatest at an intermediate amount of canopy cover—at a value that is often less than 50% woody canopy cover because of the influence that woody plants have on adjacent intercanopy patches (also referred to as the degree of “connectivity”; Fig. 1B; Breshears, 2006). Aeolian sediment transport and associated wind erosion are likely related to the amount of woody plant cover in an ecosystem because woody plants are generally the predominant “roughness elements”. The height, width and spacing of the main roughness elements in an ecosystem determine the predominant way in which vegetation influences the vertical wind profile to produce one of three types of flow: isolated roughness, wake interference, or skimming (Lee and Soliman, 1977; Lee, 1991a,b; Wolfe and Nickling, 1993; Fig. 2). In addition to serving as roughness elements, woody plants often increase ground cover via large inputs of litter to the ground beneath the plant canopy. Consequently, the effects of woody plants on aeolian processes (Aguiar and Sala, 1999; Okin and Gillette, 2001) represent an important, but perhaps somewhat under-appreciated, linkage between ecology and geomorphology (Urban and Daniels, 2006).

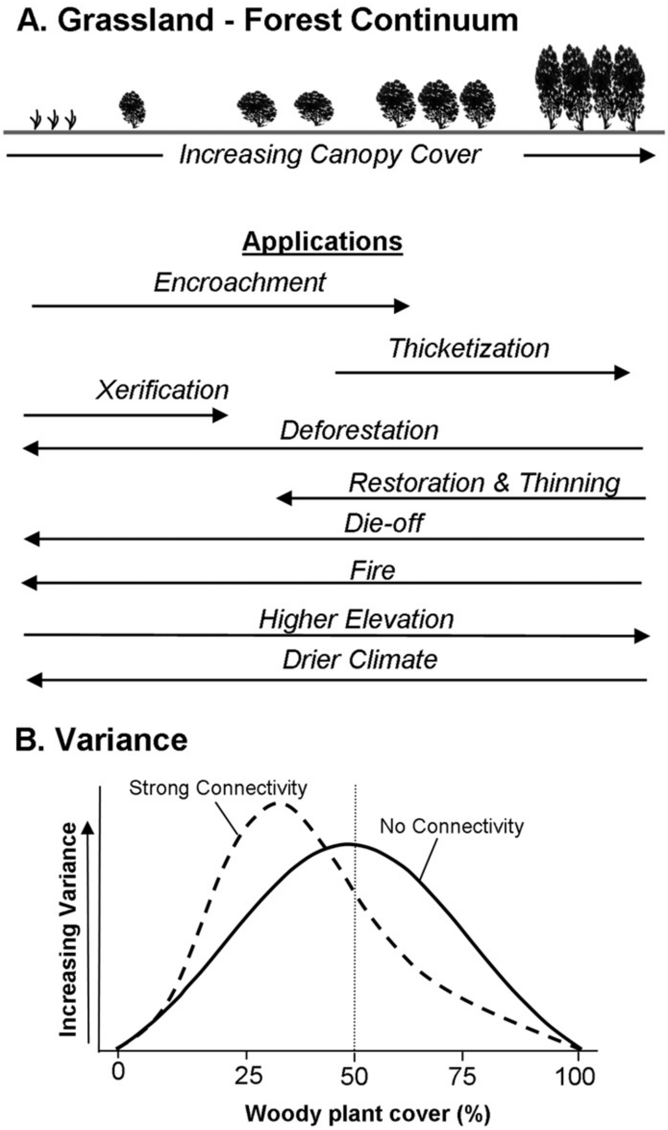

Fig. 1. (A) The grassland–forest continuum as a gradient of increasing cover by woody plants (and co-occurring increases in woody plant height), spanning shrublands and woodlands with intermediate levels of woody plant cover. The mean and variance of ecosystem properties related to energy, water, and biogeochemistry (e.g. carbon) are hypothesized to exhibit trends along the continuum. Relevant environmental issues include encroachment of woody plants, thicketization in which savannas become woodlands, xerification or desertification, deforestation, restoration and thinning, die-off of woody plants, and fire. Increases in elevation and/or changes to a wetter climate often result in an increase woody plant canopy cover; conversely, decreases in elevation and/or a drier climate often result in a decrease in woody canopy cover (except in the case of xerification). (B) Variance in many ecosystem properties is hypothesized to be greatest at an intermediate amount of canopy cover; this value is often less than 50% woody canopy cover because woody plants have strong connectivity with the adjacent intercanopy patches, a concept that is applicable to near-surface wind flows (modified from Breshears, 2006).

Despite the overall importance of aeolian processes in dryland ecosystems, variability in aeolian sediment transport as a function of woody plant cover along the grassland–forest continuum has yet to be systematically evaluated. The goal of this paper is to address this issue. The specific objectives are: (1) compile measurements of aeolian sediment transport as a function of woody plant canopy cover for undisturbed and disturbed sites (from published studies and other measurements reported here), (2) evaluate relevant interrelationships between boundary layer flows and land surface characteristics associated with woody plant cover, and (3) propose a general framework for aeolian sediment transport that builds on three key findings that emerged from objectives 1 and 2—(i) among relatively undisturbed ecosystems, shrublands have inherently greater aeolian sediment transport; (ii) for disturbed ecosystems, the upper bound for aeolian sediment transport decreases with increasing amounts of woody plant cover because of the height and density of the canopy effects on airflow patterns and because the total amount of ground cover generally increases with woody plant cover; and, (iii) grasslands and other systems with few woody plants span the largest range of rates for aeolian sediment transport and have the largest values after disturbance, shrublands have inherently large rates for aeolian sediment transport that can be increased moderately by disturbance, and woodlands and forests have smaller rates, even following disturbance. The implications of the conceptual framework are discussed relative to major environmental challenges that include land degradation and desertification,

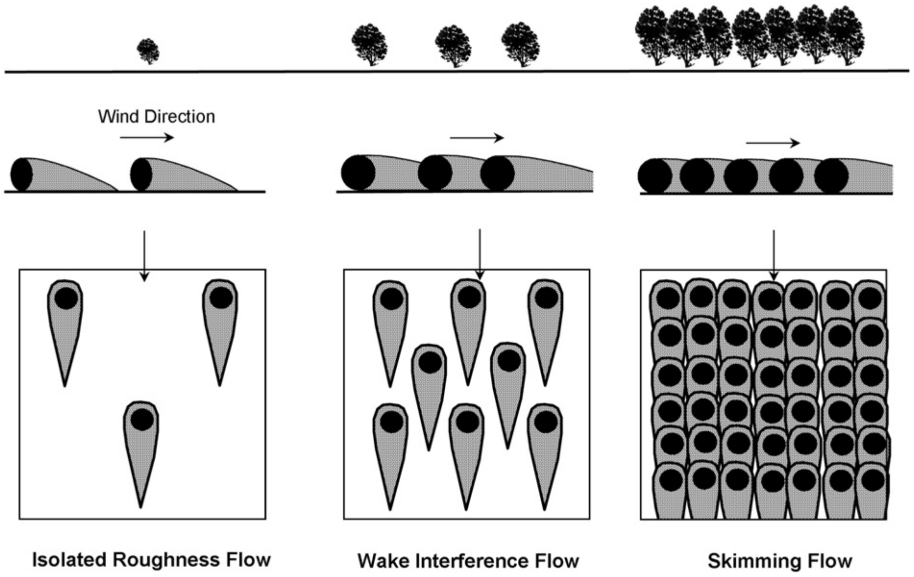

Fig. 2. Three major types of flow regimes related to woody plant density (top): (a) isolated roughness flow, for <16% canopy cover; (b) wake interference flow, for 16–40% canopy cover; and (c) skimming flow, for >40% canopy cover, as seen in profile (center) and from above (bottom; modified from Wolfe and Nickling, 1993).

dust storms, contaminant transport, and alterations of the hydrological cycle.

2. Compilation of measurements along the grassland–forest continuum

2.1. Methods and measurements

Estimates of aeolian sediment transport, expressed as mass flux transported in the horizontal direction (g m^{-2} d^{-1}), were compiled from published studies and from new measurements (detailed below) for ecosystems with variable coverage of woody plants. Estimates were categorized as either relatively undisturbed sites or sites that had severe recent disturbance, including agricultural sites, scraped sites, burned sites, sites with extensive military tracks, and sites that were so degraded through historical grazing and other land use that essentially no herbaceous cover remained between woody plants. Estimates were included if field measurements were obtained using Big Spring Number Eight samplers (BSNE; see Fryrear, 1986). One study that used a Bagnold-type sampler was also included because a comparison with BSNE samplers indicated that these two types of samplers provided estimates of aeolian sediment transport that were within 10% of each other (Breshears et al., 2003). Measurement intervals spanned from 3 to 30 months. Studies that focused on individual events or were conducted using wind tunnels were not included. In several cases, estimates of sediment transport were calculated from data provided in the original studies and converted to a daily basis. Spatial density of roughness elements (see Section 3.1 below) was calculated using percent woody plant cover, height, and mean plant diameter, all of which were available for most sites. For some sites woody plant cover was estimated from photos of the site or inferred from the text. In two cases where plant height was not reported, an approximate height associated with the woody plant species was assumed. Height and mean plant diameter were available for several of the sites that spanned from small (~5%) to large (72%) amounts of canopy cover. A predictive equation, derived from sites with available data, was applied to sites where mean canopy diameter was missing: $\text{diameter} = 1.44(\text{height})^{0.44}$ ($r^2 = 0.97$). Where sediment transport was reported for multiple measurement heights, the rates were averaged over the available heights to provide an approximate estimate of mean sediment transport up through 1 m above ground. Disturbed sites were evaluated with respect to pre-disturbance canopy cover. In particular, canopy cover for burned sites included standing, burned, and sometimes dead trees as part of canopy cover. Although some woody plants had lost foliage, the woody branching structure can still be considered a roughness element. For one type of less common disturbance, tree thinning with heavy machinery in which tree cover and ground cover were substantially reduced, pre- and post-disturbance values of canopy cover were evaluated.

Aggregated estimates of sediment transport from ongoing studies were included to supplement the overall assessment given the few such measurements in grasslands and woodlands (Breshears et al., 2003; Vermeire et al., 2005; but see Baker and Jemison, 1991; Baker et al., 1995). These studies focus on estimating aeolian sediment transport in the context of land disturbances and contaminant transport (more detailed evaluations of these data sets will be reported elsewhere). Sediment transport was measured for periods spanning 10–12 months for three of the sites and 30 months for the fourth site (Frijolito; see below). Measurements for all four sites were obtained using BSNE samplers (Zobeck et al., 2003) at various heights up to 1 m and collected roughly every 1–2 weeks. Samples were collected, dried, and weighed. Sampling intervals that were confounded by rainsplash as described in Whicker et al. (2006a) were eliminated from the analysis. All four sets of new measurements were obtained during a period of intense drought, which was severe enough to trigger extensive mortality of piñon trees at or near the northern New Mexico, USA sites (Breshears et al., 2005a; Rich et al., 2008). Estimates of sediment transport ranged from 0.17 to 4.85 g m^{-2} d^{-1} (Table 1) across the four study sites:

- *Santa Rita Experimental Range (SRER), Sonoran desert grassland, Arizona, USA*. The first grassland site was a Sonoran desert grassland dominated by the non-native annual grass *Eragrostis lehmanniana* (Lehman lovegrass) with a small amount of shrub cover from *Prosopis velutina* (velvet mesquite). The field plots were located within the University of Arizona pasture cell at SRER, where long-term vegetation change and grazing and management impacts have been studied for more than a century (McClaran, 2003). Sediment transport at SRER was the greatest of the four new estimates, even though ground cover was substantial (60%): 4.85 g m^{-2} d^{-1} (Field et al., manuscript in preparation).
- *Area J, semiarid grassland on a landfill at Los Alamos National Laboratory New Mexico, USA*. The second grassland site had no woody plant cover; much of the herbaceous cover was *Bouteloua gracilis* (blue grama), which had been established in the topsoil with irrigation in previous

Table 1
Sediment transport measured in undisturbed ecosystems using BSNE and Bagnold samplers

Study sites	Dominant vegetation	Woody canopy cover (%)	Woody canopy height (m)	Canopy diameter (m)	Spatial density (*C*)	Ground cover (%)	Soil texture	Mean precipitation (mm)	Mean wind speed (height) ($m\ s^{-1}$)	Sediment transport ($g\ m^{-2}\ d^{-1}$)	References
Grassland											
Rocky Flats, CO,USA	*Bouteloua gracilis*	0	0	0	N/A	79	Clay	370	2.1	1.67[a]	Breshears et al. (2003)
Area J, NM,USA	*Bouteloua gracilis*	0	0	0	N/A	38	Sandy loam	400	2.3	1.4	This study
SRER, AZ,USA	*Eragrostis lehmanniana*	~5	2	2	0.003	~60	Sandy loam	350	2.7 (1 m)	4.85	Field et al. (in preparation)[b]
Shrubland and woodland											
WIPP, NM, USA	*Larrea tridentate*	28	0.75	1.2	0.09	66	Sand	300	2.6	27.4[a]	Whicker et al. (2002), Breshears et al. (2003)
Oklahoma, USA	*Artemisia filifolia*	35	1	1.437	0.20	NA	Loamy fine sand	602	NA	4.28	Vermeire et al. (2005)
Frijolito, NM, USA	*Pinus edulis, Juniperus monosperma*	45	3.21	2.34	0.92	62.12	Sandy loam	400	1.0 (1 m)	3.0	This study
Mesita del Buey, NM,USA	*Pinus edulis, Juniperus monosperma*	46	4	3	0.97	NA	Sandy loam	400	1.0 (1 m)	1.1	This study
Forest											
LANL, NM,USA	*Pinus ponderosa*	75	12	4	27.00	98	Silt loam	500	0.8 (1 m)	0.17[a]	Breshears et al. (2003)
LANL, NM,USA	*Pinus ponderosa*	75	12	4	27.00	98	Silt loam	500	0.5 (1 m)	0.738	Whicker et al. (2006a,b)

[a] Dust was collected using Bagnold samplers.

[b] Manuscript in preparation.

years and then equilibrated with ongoing climate. Vegetation on the landfill cover included native and non-native herbaceous species. Early successional vegetation cover on landfills in this area (Breshears et al., 2005b) is similar to herbaceous vegetation in neighboring woodlands (Martens et al., 2001) and shares the same dominant herbaceous species as shortgrass steppe ecosystems within the region (Lauenroth and Sala, 1992). Additional details on the site and measurements are available in Whicker and Breshears (2004). Mean daily sediment transport at this site was less than a third of that at the SRER grassland: 1.4 $g\ m^{-2}\ d^{-1}$.

- *Mesita del Buey, piñon–juniper woodland at Los Alamos National Laboratory, New Mexico, USA*. The Mesita del Buey woodland site is an intensively studied site dominated by piñon (*Pinus edulis*) and juniper (*Juniperus monosperma*; see Breshears, 2006, 2007 and references therein). The site is located at Technical Area 54 within Los Alamos National Laboratory Environmental Research Park. Additional details on site and measurements are reported in Whicker and Breshears (2004). This woodland site had the smallest sediment transport of the four new estimates: 1.1 $g\ m^{-2}\ d^{-1}$.
- *Frijolito, piñon–juniper woodland site within Bandelier National Monument, New Mexico, USA*. The Frijolito woodland site is also an intensively studied site that was originally forest dominated by *Pinus ponderosa* (ponderosa pine) but was transformed into piñon–juniper woodland (*Pinus edulis* and *Juniperus monosperma*) when nearly all *P. ponderosa* trees died during a drought in the 1950s (Allen and Breshears, 1998). As noted above, this site was subsequently impacted by a second severe drought beginning around 2000 (as was Area J and Mesita del Buey) that resulted in extensive *P. edulis* mortality during the measurement interval (Breshears et al., 2005a). The mean sediment transport at Frijolito was 3.0 $g\ m^{-2}\ d^{-1}$.

2.2. Relatively undisturbed sites

For relatively undisturbed dryland sites along the grassland–forest continuum, mean sediment transport ranged from as little as 0.17 $g\ m^{-2}\ d^{-1}$ to as much as 27.4 $g\ m^{-2}\ d^{-1}$ (Table 1). The sites ranged from 0 to 75% woody canopy cover and from 38 to 98% ground cover. The maximum measured flux was from a shrubland site that had 28% woody canopy cover and overall ground cover that exceeded 65% (Fig. 3). The rate of transport in relatively undisturbed grasslands and woodlands was less than those for shrubland sites and exceeded those for forests. These results suggest an overall trend in sediment transport related to variation in woody plant cover for grasslands, shrublands, woodlands, and forests and are similar to those hypothesized by Breshears et al. (2003) based on a subset of this data set that included single estimates each from a grassland, a shrubland, and a forest.

2.3. Disturbed sites

For disturbed sites along the grassland–forest continuum, sediment transport ranged from 1.1 $g\ m^{-2}\ d^{-1}$ to 6002 $g\ m^{-2}\ d^{-1}$ with sites ranging from 0% to 72% canopy cover (Table 2). Sediment transport at disturbed sites varied substantially among sites with different amounts of woody plant cover and generally exceeded fluxes for undisturbed sites with comparable amounts of woody plant cover. Notably, observations from disturbed sites suggest that an upper bound exists to sediment transport and this upper bound decreases with increasing canopy cover (Fig. 3, solid symbols). Grasslands and other systems with little or no woody canopy cover (e.g., bare areas or agricultural fields) have the widest range of potential sediment transport, with the variation within this range being associated with variation in the amount of intercanopy ground cover from herbaceous plants (Okin et al., 2006) and biological and non-biological soil crusts (Belnap, 2003). Shrublands have inherently larger sediment transport that can be increased by disturbance. In contrast, woodlands and forests have smaller rates of sediment transport, even following disturbance. Sediment transport at the thinned ponderosa pine forest site (diamonds in Fig. 3) could be associated with either of two values of cover, both of which are near the lower limit trend line for undisturbed systems. Overall, the trends are consistent with previous observations that large sediment transports are associated with a specific range of values for the spatial density of roughness elements (woody plants in this case), as discussed below.

Surprisingly, no clear trends appeared related to soil texture within the limited available data sets (Tables 1 and 2). Rates of wind erosion from wind tunnel studies demonstrate relationships with soil texture

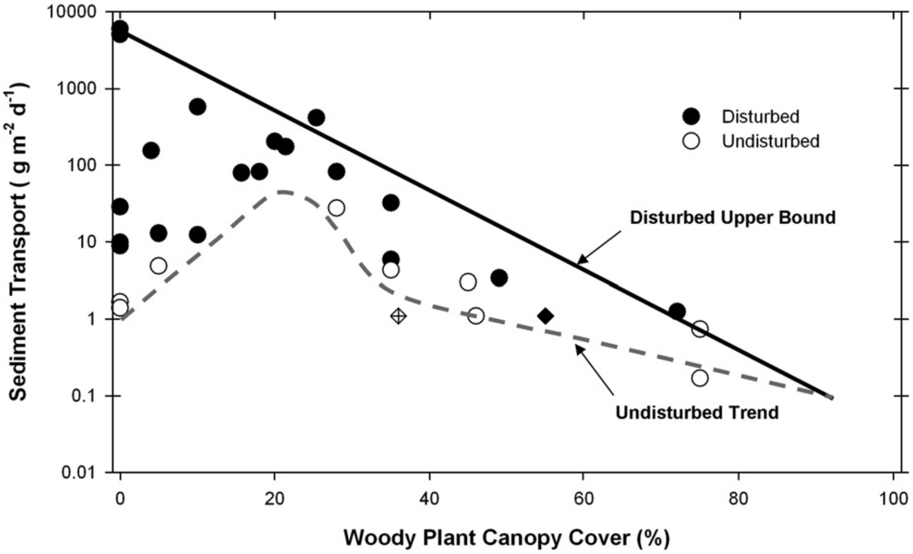

Fig. 3. Aeolian sediment transport, based on multi-month estimates of sediment transport (g m^{-2} d^{-1}), as related to woody canopy cover along the grassland–forest continuum for relatively undisturbed sites (open symbols, from Table 1) and disturbed sites (solid symbols, from Table 2). A forest site that was thinned (diamonds) is shown at pre- (solid) and post- (open with *x* inset) thinning values for canopy cover.

(Pye, 1987; Toy et al., 2002), and soil texture differences have been discussed relative to rates of wind and water erosion in grassland, shrubland and forest ecosystems (Breshears et al., 2003). The synthesis here did not detect any clear effects of soil texture.

3. Interrelationships between boundary layer flows and land surface characteristics

Variation in land surface characteristics and associated effects on flow regimes influences aeolian sediment transport. Of particular relevance are trends in flow regimes, shear stress, and surface erodibility.

3.1. Flow regimes

The woody plant mosaics associated with sites along the grassland–forest continuum fundamentally influence airflow regimes (Fig. 2). Woody plants interact with wind flow in the atmospheric boundary layer, altering speed, direction, and turbulence structure. A single, isolated plant alters wind flow by imparting frictional force against the wind, which retards the flow and transfers energy and momentum to branches and leaves. In addition, the fluid is accelerated around the sides and top of the plant, and turbulent eddies are created in the wake of the plant (this influence provides potential "connectivity" between woody plants and the areas around them, as defined above and in Fig. 1; Breshears, 2006). Wind flow through stands of vegetation at larger ecosystem or landscape scales reflects the combined effects of individual plants and generally has been grouped into one of three flow regimes: 1) isolated roughness flow, 2) wake interference flow, or 3) skimming flow (Wolfe and Nickling, 1993; Fig. 2). Isolated roughness flow is characterized as having flows and wakes that act in isolation of one another and occurs in ecosystems with small plant densities (<16% canopy cover). Wake interference flow is associated with the wakes that form when the wind and plant interactions begin to interfere with one another, occurring at plant densities of approximately 16 to 40% canopy cover. Skimming flow is associated with conditions in which winds skim across the top portions of plants, with little wind energy diverted to the soil surface and, therefore, resulting in little wind erosion. This type of flow generally occurs when plant canopy cover exceeds 40%.

In addition to woody plant cover, the shape and spacing of plants are important characteristics of canopy architecture that influence wind flow through vegetation. Roughness density has been used extensively to relate canopy architecture and surface roughness (Raupach et al., 1993). Roughness density, λ, is defined as:

$$\lambda = \frac{nbh}{A}, \tag{1}$$

where *n* is the number of plants, *b* is the base diameter, *h* is the plant height, *bh* is the frontal area of the plant, and *A* is total area. Assuming uniformly and isotropically distributed vegetation, the fraction of the area with canopy cover (F_c), as viewed from above, is exponentially related to λ (Fryrear, 1985; Findlater et al., 1990):

$$F_c = 1 - e^{-\lambda}. \tag{2}$$

Another parameter that describes the interaction of wind and vegetation is the concentration of roughness elements, or the dimensionless *C* value (Raupach et al., 1980; Warner, 2004). The *C* value is slightly different from λ in that it normalizes the frontal area of the plants to the square of the distance (*d*) between the plants rather than to the size of the area (as shown in Eq. (1)):

$$C = \frac{hb}{d^2}. \tag{3}$$

As with λ, the *C* value is related to canopy cover. Again, by assuming an even and isotropic distribution of woody plants, the *C* value can be rewritten in terms of F_c:

$$C = \frac{h}{b^2}\left(\frac{F_c}{1 - F_c}\right)^2, \tag{4}$$

λ and *C* are related to F_c, and thus also to shear stress, as shown below.

3.2. Shear stress partitioning

Vegetation cover and the soil surface extract momentum from near-surface wind, resulting in shear stress (τ), which is defined as a tangential force applied per unit surface area. Total shear stress can be partitioned between the vegetation and the surface soil as (Raupach et al., 1993):

$$\tau = \rho u_* = \tau_v + \tau_s, \tag{5}$$

where ρ is the density of air, u_* is the friction (or shear) velocity, τ_v is the shear stress apportioned to vegetation, and τ_s is the shear stress

Table 2
Sediment transport in disturbed ecosystems measured using BSNE samplers

Study sites	Dominant vegetation/ disturbance	Woody canopy cover (%)	Woody canopy height (m)	Canopy diameter (m)	Spatial density (C)	Ground cover (%)	Soil texture	Mean precipitation (mm)	Mean wind speed (height) (m s^{-1})	Sediment transport ($\text{g m}^{-2}\text{ d}^{-1}$)	References
Grassland/cultivated											
Banizoumbu, Niger	*Hordeum vulgare*/ cultivated	0	0	0	NA	NA	Sand	500	10[a] (2 m)	5060[b]	Bielders et al. (2002)
Emerson Lake, CA, USA	Scrub/military tracking	0[c]	0	0	NA	NA	Clay	70[d]	NA	9.8[e]	van Donk et al. (2003)
Jornada, NM, USA	*Prosopis glandulosa*/ scraped	0	0	0	NA	NA	Loamy sand to sandy loam	247	3[f]	6002[g]	Gillette and Pitchford (2004)
Khanasser, Syria	*Hordeum vulgare*/ cultivated	0	0	0	NA	NA	Sandy loam	200	4[h] (2 m)	28.5	Masri et al. (2003)
Khanasser, Syria	Grassland/ Grazing	0	0	0	NA	NA	Sandy loam	200	4[h] (2 m)	8.9	Masri et al. (2003)
Shrubland and woodland											
Banizoumbou, Niger	*Guiera senegalensis*/ grazing	4[i]	2[i]	0	NA	Dense	Sand	500	10[i] (2 m)	154[i]	Bielders et al. (2002)
Lavic Lake, CA, USA	Scrub/military tracking	5[c]	0.5[c]	0	NA	NA	Sandy loam	70[d]	NA	12.9[e]	van Donk et al. (2003)
Lead Mountain, CA, USA	Scrub /military tracking	10[c]	0.5[c]	1.06	0.006	NA	Loamy sand	70[d]	NA	12.2[e]	van Donk et al. (2003)
Gypsum, CA, USA	Scrub/military tracking	10[c]	0.8[c]	1.3	0.008	NA	Sand	70[d]	NA	576.5[e]	van Donk et al. (2003)
MWELL site, NM,USA	*Prospis glandulosa*, *Ephedra trifuca*/ grazing	15.7	0.5	1.06	0.016	15.7	Fine sandy loam	247	3[f]	79.2[g]	Gillette and Pitchford (2004)
WIPP, NM, USA	*Larrea tridentate*	18	1.32	1.62	0.057	66	Sand	300	2.6	82.2	Whicker et al. (2002), Breshears et al. (2003)
Prospect, CA, USA	Scrub/military tracking	20[c]	0.8[c]	0.8	1.3	0.038	Sand	70[d]	NA	203.3[e]	van Donk et al. (2003)
MRABB site, NM, USA	*Prospis glandulosa*, *Ephedra trifuca*/ grazing	21.4	1.2	1.56	0.057	21.4	Fine sand to loamy fine sand	247	3[f]	173.5[g]	Gillette and Pitchford (2004)
MNORT site, NM, USA	*Prospis glandulosa*, *Ephedra trifuca*/ grazing	25.4	1	1.44[b]	0.081	25.4	Fine sand to loamy fine sand	247	3[f]	412.1[g]	Gillette and Pitchford (2004)
Oklahoma, USA	*Artemisia filifolia*/ spring burned	35	1	1.437	0.20	NA	Loamy fine sand	602	NA	5.9	Vermeire et al. (2005)
Oklahoma, USA	*Artemisia filifolia*/ autumn burn	35	1	1.437	0.20	NA	Loamy fine sand	602	NA	32.1	Vermeire et al. (2005)
Forest											
LANL, NM, USA	*Pinus ponderosa*/ thinned	36[j]	12	4	0.949	86	Silt loam	500	0.8 (1 m)	1.1[k]	Whicker et al. (2007a)
LANL, NM, USA	*Pinus ponderosa*/ thinned	55[l]	12	4	0.949	86	Silt loam	500	0.8 (1 m)	1.1[k]	Whicker et al. (2007a)
LANL, NM, USA	*Pinus ponderosa*/ severe burned	49	12	4	2.769	NA	Silt loam	500	0.8 (1 m)	3.4[k]	Whicker et al. (2006a)
LANL, NM, USA	*Pinus ponderosa*/ moderate burned	72	12	4	19.837	NA	Silt loam	500	0.8 (1 m)	1.3[k]	Whicker et al. (2007a)

[a] Average over duration from Table 1 in Bielders et al. (2002).
[b] Re-calculated from Tables 2 and 3 in Bielders et al. (2002).
[c] Estimated from Fig. 2 in van Donk et al. (2003).
[d] Average of the range between 35 and 130 mm reported in van Donk et al. (2003).
[e] Daily average re-calculated based on the total sediment discharge in entire period.
[f] Estimated from Dauses et al. (http://usda-ars.nmsu.edu/presentations/DauesAeolianProcesses.pdf; verified Oct. 9, 2007).
[g] Interpolated from Fig. 7 in Gillette and Pitchford (2004).
[h] Average values of wind speed during summer and is re-calculated from Table 3 (Masri et al., 2003).
[i] Estimated from site description in Bielders et al. (2002).
[j] Woody canopy coverage after thinning.
[k] Estimated from mean values for dry periods from data in associated reference.
[l] Woody canopy coverage before thinning.

apportioned to the surface, or in this case the soil surface. The relationship between λ and C with respect to τ and τ_v is such that as λ and C increase, the ratio of τ_v to τ goes towards one. That is, as vegetation roughness increases, a greater portion of total shear stress is caused by the vegetation relative to the soil surface.

The parameter τ_s in Eq. (5) can be rewritten in terms of shear stress normalized to stress on bare surface areas only (Raupach et al., 1993):

$$\tau_s = \tau_s'(1-F_c), \tag{6}$$

where τ'_s is the shear stress on bare ground only. Further, the total shear stress for partially vegetated areas can be portioned into two surface components, woody (τ_{woody}) and herbaceous vegetation (τ_{grass}):

$$\tau_v = \tau_{\text{woody}} + \tau_{\text{grass}}, \tag{7}$$

or in terms of stress only on plant surfaces,

$$\tau_v = F_c(\tau'_{\text{woody}} + \tau'_{\text{grass}}). \tag{8}$$

3.3. Relationship between flow regime and erodibility

The interaction between airflow, vegetation and soil surface drives the aeolian erodibility of a landscape, and can be described in terms of the metrics λ, *C*, and τ, all of which vary along the grassland–forest continuum. In "ideal" grasslands with only herbaceous cover, Eq. (8) can be simplified from $\tau_v=F_c(\tau'_{\text{woody}}+\tau'_{\text{grass}})$ to $\tau_v=F_c\tau'_{\text{grass}}$ because woody plants are largely absent. In undisturbed grasslands, F_c can be quite large although the shear stress from individual herbaceous plants is expected to be small compared to that from woody vegetation, which is typically taller and wider. In grasslands, λ and *C* values have small *h* and *b* values that are counterbalanced by the relatively large F_c yielding larger τ_v values. The large amount of herbaceous cover present in undisturbed grasslands with no woody canopy cover likely produces skimming type airflow (Lee, 1991a,b).

Shrublands and woodlands are characterized by substantial components of woody and herbaceous plants (House et al., 2003). The woody canopy cover, F_c, in shrublands and woodlands can vary significantly, which in turn affects the partitioning of the shear stress between the woody and herbaceous components. If woody plant cover is sparser, as occurs in many shrublands, the flow regime will likely correspond to either isolated wake flow or wake interference flow, depending on the canopy cover and the height and width of the woody vegetation. Dryland sites with wake interference flow are expected to have a greater amount of shear stress transferred to the intercanopy surface, potentially causing greater aeolian sediment transport. Woodlands generally have greater amounts of woody plant cover and taller canopy heights than shrublands, such that the shear stress from vegetation generally approaches $\tau_v=F_c\tau'_{\text{woody}}$, resulting in skimming flow.

For forests, shear stress further approaches $\tau_v=F_c\tau'_{\text{woody}}$ from additional increases in height and canopy cover, such that only a few locations are not beneath woody plants. Taller tree heights and larger base diameters (including the branches and leaves/needles) result in relatively large values of roughness, λ, and spatial density, *C*. Relatively large values of basal diameters for forest trees (spanning the woody canopy patch, not just the trunk diameter) also result in a greater F_c and indicate that airflow above the tree canopy should be skimming type flow. Consequently, thickly forested areas would be expected to have lesser aeolian transport because of the tall and thick vegetation associated with the greater amount of canopy cover.

Spatial density, *C*, varied with canopy cover for the undisturbed (Table 1) and disturbed (Table 2) sites. The variation in *C*, focusing solely on the woody plants as roughness elements (i.e., ignoring the roughness effects of herbaceous plants) for relatively undisturbed sites along the grassland–forest continuum, highlights how *C* increases with canopy cover (Fig. 4A). Previous studies of wind erosion have suggested that values of *C* near 0.1 are associated with wake interference flow and large rates of wind erosion (Warner, 2004). Results presented herein are consistent with this observation (Fig. 4B). Note that *C* is near 0.1 for shrublands but generally not for the other types of ecosystems along the grassland–forest continuum. In addition, note that *C* is affected by woody canopy cover, spacing, and height and recall that the height of woody plants often increases with woody plant cover along the grassland–forest continuum (Fig. 1; e.g., Martens et al., 2000). Consequently, only shrublands, which often have relatively small amounts of woody canopy cover (~20–30%) and are composed of relatively low stature woody plants, intersect the values of *C* near 0.1 (Fig. 5), where aeolian sediment transport and associated wind erosion are thought to be greatest.

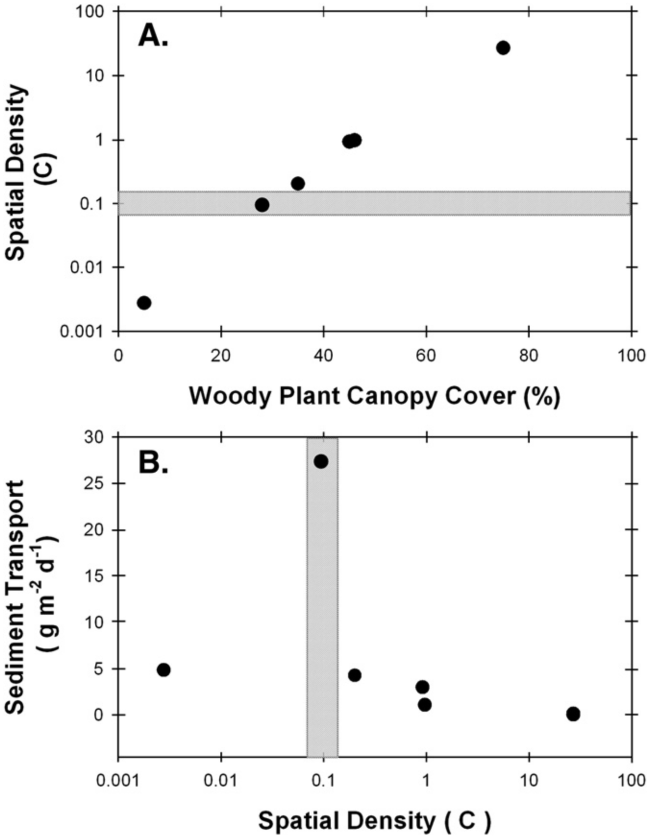

Fig. 4. A. Estimates of spatial density *C* for relatively undisturbed sites (Table 1) as a function of canopy cover; *C* as calculated here is based on woody plants as roughness elements and ignores the finer-scale roughness associated with herbaceous plants. B. Values of *C* near 0.1 have been hypothesized to be associated with larger rates of sediment transport.

4. A new conceptual framework for aeolian sediment transport along the grassland–forest continuum

4.1. Model description

The available data suggest two trends in how aeolian sediment transport varies along the grassland–forest continuum (Fig. 6). Firstly, for relatively undisturbed ecosystems, shrublands have inherently greater sediment transport potential, likely because of wake interference flow associated with the spatial concentration of roughness elements. Secondly, for disturbed ecosystems, the upper bound for sediment transport decreases with increasing amount of woody plant cover, probably because of effects of canopy height and density on airflow patterns and because the minimum amount of ground cover at a site tends to increase as woody plant cover increases. That is, ground cover is interrelated with, and directly proportional to, woody plant cover. Because woody plants represent a substantial concentration of biomass and generate large amounts of litter, the ground cover directly beneath woody plants generally is completely covered with litter. Consequently, woody canopy cover also often determines a minimum amount of ground cover for an ecosystem. That is, as woody canopy cover increases along the grassland–forest continuum, so does minimum amount of ground cover. For example, a site with 80% tree cover, should have at least 80% ground cover, and so intercanopy cover

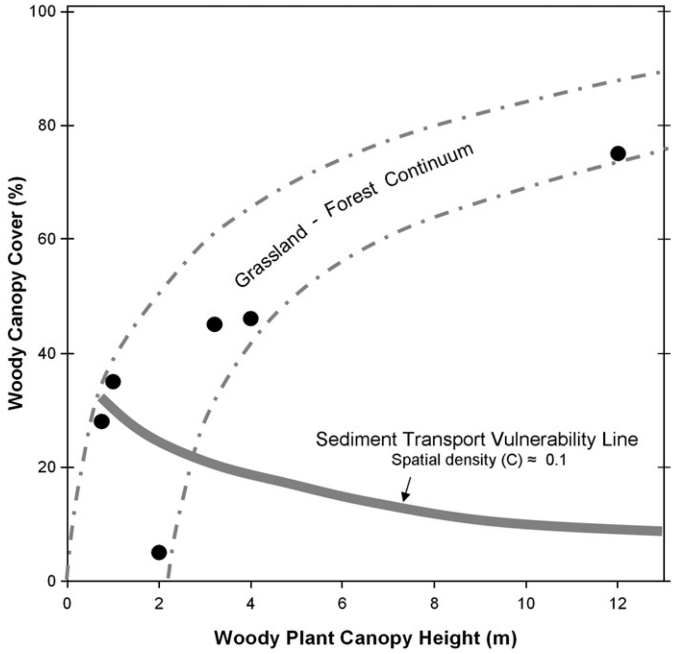

Fig. 5. Relatively undisturbed sites along the grassland–forest continuum as a function of canopy cover and height (dashed lines correspond to an approximate envelope around sites spanning the grassland–forest continuum) and values of woody canopy cover and height resulting in a spatial density *C* near 0.1 (solid line), associated with large rates of erosion, as a function of woody canopy cover and height.

can range only from 0–20%. In addition, woodlands and forests also are likely to have skimming flow because they are associated with >40% cover. Under unusual circumstances, more ground cover may be associated with the undisturbed trend line, in which case aeolian sediment transport can be less than that associated with that trend line. In addition, although soil particle sizes certainly affect aeolian sediment transport (Pye, 1987; Toy et al., 2002), within the broad perspective of the framework presented here, trends associated with woody plant cover are evident whereas expected trends with soil texture (e.g., Breshears et al., 2003) are not. This suggests that woody plant cover may be an equally important factor in controlling rates of aeolian transport at the regional to global scales for which woody plant cover varies greatly among drylands. Soil texture likely will explain additional variance in sediment transport potential within the proposed framework. Additional studies are needed to further test the trends hypothesized within the framework and for modifications because of soil texture.

4.2. Implications, applications and future directions

The proposed conceptual framework requires additional testing but offers promise for addressing numerous key environmental issues related to aeolian processes. For example, the framework may be applicable to large-scale efforts to manage ground cover and provide shelter belts to reduce dust storms, as is currently being done in China (Shao and Dong, 2006; Zhao et al., 2006). More specifically, the framework suggests that increasing shrub cover could reduce wind erosion at bare sites, but that adding shrub cover to sites with existing

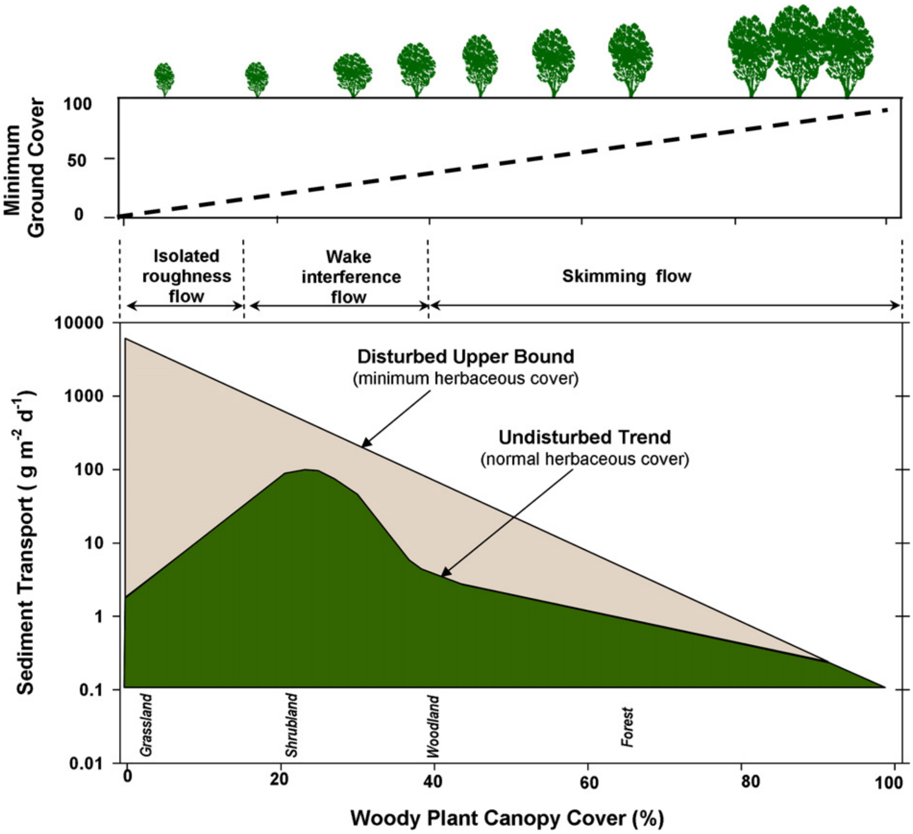

Fig. 6. Conceptual framework for aeolian sediment transport as sediment transport along the grassland–forest continuum for undisturbed and disturbed sites. Also depicted are minimum amount of ground cover (assumed here to equal woody plant cover) and main types of flow. Relatively undisturbed sites occur near the undisturbed trend line. Disturbances can increase sediment transport toward an upper bound. Among relatively undisturbed ecosystems, shrublands inherently have the largest sediment transport. The range of values between the undisturbed trend line and the disturbed upper bound is greatest for grasslands. Variation in sediment transport between the undisturbed trend line and the disturbed upper bound is associated with changes in amount of ground cover in intercanopy areas, particularly from herbaceous plants but also including biological and non-biological soil crusts. Variation in soil texture may also influence variation within this interval. Unusually large amounts of intercanopy ground cover can yield sediment transport that are less than corresponding values on the undisturbed trend line.

herbaceous cover could, in some cases, result in increased aeolian sediment transport and associated wind erosion. The framework also suggests that establishing larger trees with sufficient density, if feasible, could simultaneously decrease aeolian sediment transport, increase rates of dust deposition and improve soil quality (Shirato et al., 2004; McGowan and Ledgard, 2005).

The proposed framework also has important implications for atmospheric modeling. One of the central uncertainties in atmospheric models is dust flux, yet few field data exist on atmospheric dust flux. The reported synthesis is insufficient to address this issue in a robust way but can serve as a starting point for linking sediment transport near the ground to vertical dust flux inputs for atmospheric models. The relationship between sediment transport (horizontal flux) and vertical dust flux varies with site conditions (e.g., vegetation cover) and has particle size dependencies (e.g., PM10 as in Gillette, 1997; Whicker et al., 2006b). At the risk of oversimplifying these relationships, estimates from Whicker et al. (2006a) suggest that vertical dust flux may be as large as 5% of sediment transport. Building on this assumption, mean daily sediment transport for general land surface categories are proposed that may be relevant to large-scale atmospheric models: undisturbed forests, disturbed forests, undisturbed woodlands, disturbed woodlands, relatively undisturbed shrublands, disturbed shrublands, undisturbed grasslands, moderately disturbed grasslands, essentially bare areas (sites with no herbaceous or woody plant cover), and areas that have unusually large amounts of ground cover within semiarid settings (Fig. 7).

The proposed conceptual framework (Fig. 6) and its extension (Fig. 7) also has implications that span from applied issues, related to contaminant transport and associated risks, to more fundamental issues related to biogeochemical, hydrological and ecological processes that underlie challenges related to global climate change and land use. The need to assess potential contaminant transport has motivated many of the recent studies of aeolian sediment transport (Whicker et al., 2002; Breshears et al., 2003; Whicker et al., 2006a,b, 2007a,b). Findings relevant to contaminant transport that affect respirable fractions of airborne contaminants and associated doses, in addition to the estimated sediment transport themselves, include documenting a direct relationship between sediment transport and PM10 concentrations (Whicker et al., 2006a) and quantifying site-specific and particle-size-dependent variation in partition coefficients (K_ds) for U in surface soils (Whicker et al., 2007b). The framework also has biogeochemical implications relevant to how resources are redistributed within and among ecosystems (Reynolds et al., 2001; Neff et al., 2005; Reynolds et al., 2006a,b,c). Indeed, nutrient losses and redistribution by aeolian processes are viewed as key components of desertification and degradation processes (Schlesinger et al., 1990; Aguiar and Sala, 1999; Peters et al., 2006). In addition, the potential relationships between sediment transport and vertical dust flux, described above in the context of atmospheric processes, has fundamental hydrological implications. For example, vertical dust flux and subsequent transport at regional scales can lead to inhibition of precipitation (Rosenfeld et al., 2001) and to hastening of snowmelt (Painter et al., 2007).

5. Conclusions

A more comprehensive understanding of how aeolian sediment transport and associated wind erosion and dust flux vary along the grassland–forest continuum is needed to better assess trends across a broad spectrum of ecosystem types and in associated responses to disturbance. Estimates of sediment transport along the grassland–forest continuum, which have been largely lacking until recently, seem to be bounded within an envelope related to woody plant cover and site disturbance. New data in conjunction with previously reported estimates for sites along the grassland–forest continuum that have not been recently and/or drastically disturbed suggest that aeolian sediment transport may be inherently greater for shrublands. This result is consistent with recent evaluations of roughness elements focusing on roughness density and height to width ratios of roughness elements, which are associated with woody plants in this case. Notably, because height tends to increase with woody plant cover along the grassland–forest continuum, it is primarily low density shrublands that have maximal effects on the wind profile and on aeolian sediment transport; greater densities or taller woody plants tend to be associated

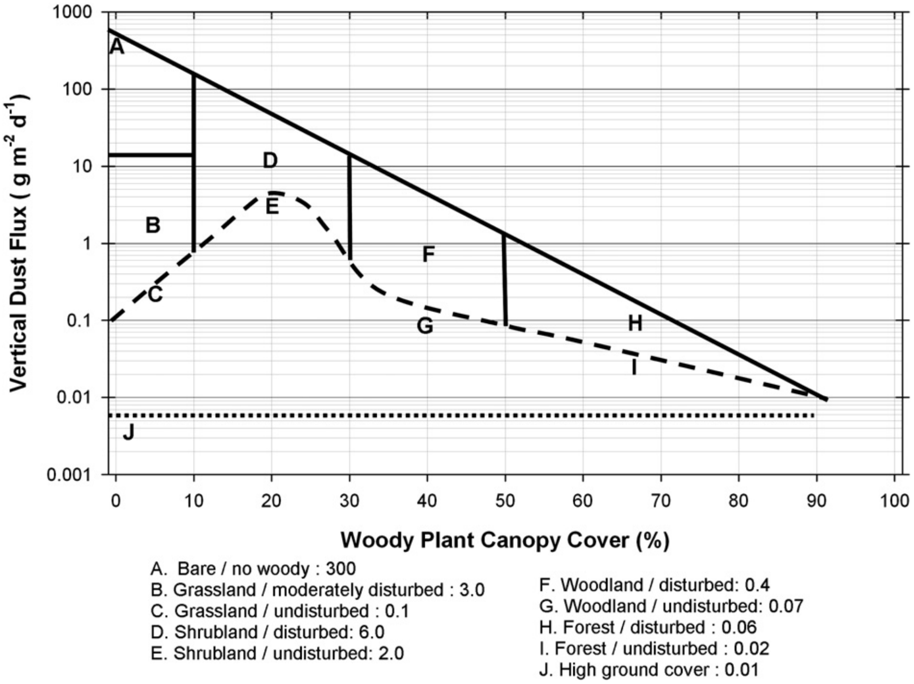

Fig. 7. Categories of vertical dust flux along the grassland–forest continuum, bounded between relatively undisturbed and disturbed sites. Estimates are based on assuming sediment transport = 5% of vertical dust flux (Whicker et al., 2006b).

with skimming flow over the woody plant canopy. In addition, the synthesis presented here highlights that for disturbed ecosystems, the upper bound for sediment transport potential decreases with increasing amount of woody plant cover. Canopy height and density affects the airflow patterns and woody plant cover influences the minimum amount of ground cover. Consequently, grasslands or associated systems with no woody plants can have the largest potential for sediment transport and can span the largest range of values. Shrublands have inherently large sediment transport potential that can be increased by disturbance, and woodlands and forests have the smallest sediment transport potential, even following disturbance. These trends are consistent with previous observations that wind erosion is greatest for systems with a specific range of values of spatial density of roughness elements, woody plants in this case. The proposed framework has implications for predictions of land surface inputs of dust for atmospheric models, land management planning for reducing dust storms and associated wind erosion, and biogeochemical and contaminant transport within and across ecosystems along the grassland–forest continuum that span much of the terrestrial biosphere.

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